U.S. DEPARTMENT OF AGRICULTURE

FOREST SERVICE

WASATCH NATIONAL FOREST

ALTA AVALANCHE STUDY CENTER

Project B

Report No. 2

MECHANICAL PROPERTIES OF THE SOFT SLAB

by

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June 1967

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Much progress has been made in forecasting direct action soft slab avalanches from meterological observations. Factors such as wind, temperature and precipitation intensity are weighed against preset criteria and the hazard is judged accordingly.

However, the interplay of meterological factors is complex and standard meterological observations cannot be exclusively relied on for soft slab prediction. Ambient air temperature for example, cannot be correlated with crystal structure which is determined by upper atmospheric conditions. Also, because of radiation, air temperature may not be indicative of the metamorphism of freshly deposited snow.

With present instrumentation the forecaster is hard-pressed to keep track of the various crystal structure and property changes taking place during a storm. Besides basic changes in dendritic structure, crystal layers will vary in such important modifying features as degree of riming[4], impurity concentration, wind fragmentation, wetness, and clustering. Thus, a set of meterological conditions measured at a convenient location with convenient instruments could apply equally well to a variety of slabs which differ from one another in many mechanical properties.

Measurement of the mechanical properties of newly deposited snow are needed to supplement meterological data and improve upon the predictability of soft slab release.

There is a scarcity of experimental data pertaining to properties of newly deposited snow in the density range of 0.05 to 0.20 gm/cm^3. Most of the information which covers this low range is extrapolated from relationships derived from experiments on snow with densities greater than 0.2 gm/cm^3. Soft slab avalanches usually occur during or immediately after a storm and involve snow in this low

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density range. Laboratory experiments on fresh snow are difficult to set up, hence the development of "in situ" experimental techniques are necessary.

Two problems are encountered in the setting up of consistent "in situ" experiments. Figure 1. shows the first problem: Property and structure variation in the z-direction. To solve the first problem requires gathering data at appropriate Δz intervals. The second problem is property and structure variation in the x and y directions. The solution of the second problem involves the choice of a suitable study area, free of local wind anomolies, and the statistical design of the experiment to account for X and Y data variations.

The drop cone penetrometer

The Haefeli ram penetrometer is a convenient device for measuring the strength of the snow pack. In the Haefeli method, an impact energy is imparted to the ram and the corresponding penetration is noted. From these data, strength as a function of z can be calculated for the snow profile. These strength measurements are of great value to the avalanche forecaster in evaluating climax and deep slab hazards. However, even if the Haefeli ram is set gently on a fresh layer of snow, its narrow head may exert a pressure on an order of magnitude greater than the resistive pressure of the snow.

At the Alta Avalanche Study Center an instrument, similar in operation to the Haefeli penetrometer, was developed. This instrument, capable of measuring the strength profile of a soft slab, is the drop cone penetrometer. Previous models of this instrument have had a successful history of providing consistent fresh snow data.[1,2,3]

The sequence of operation for the Alta model (Figure 2) is as follows: The instrument rests on the snow, supported by its flange in a level position. The

cone assembly is held up by the clamp. The operator looks through the observation window, loosens the clamp, and gently lowers the cone assembly until it makes contact with the snow. The operator holds the cone assembly in this position and notes the meter stick reading, designated Z_r to symbolize reference position. The cone assembly is then lifted to an initial Z_1 reading on the meter stick, released and allowed to fall and penetrate the snow. The cone assembly comes to rest at a meter stick position recorded as Z_2. The cone assembly is then lifted and clamped in the up position, the aluminum frame is picked up and reset in a level position over a new sampling area, and the sequence is repeated.

If the weight of the cone assembly is w, the impact energy is given by:

$$U = w(Z_2 - Z_1)$$

and the penetration is:

$$Z = Z_2 - Z_r$$

Minimum input energy is obtained when

$$Z_1 = Z_r$$

U can be increased by decreasing Z_1 (i.e. raising the cone assembly since the meter stick is oriented with the 0 marking above the 1 meter marking) until the cone touches the cross bracket. For further increases in U it is necessary to add weights to the cone assembly.

Previous drop cone penetrometer models measured the diameter of the cone impression. This was a time-consuming operation and restricted the experimenters to two or three drops per determination of U. Using the construction and procedure described above enables the operator to quickly make 5 to 10 drops for each determination.

Provision was made for attaching 120, 90, 60, and 45 degree cones to the cone assembly. Comparative studies of the various cones were set up and the 60 degree cone was finally selected as most suitable for future studies. Though 120 degree and 90 degree cones gave consistent results, the diameter of these cones would have to be relatively large to allow for deep slab penetration. The 45 degree cone was disqualified because of a peculiar inconsistency; certain snows would fracture around the impact point of this narrow angle cone.

Analysis of data

As shown in figure 3., a typical run on dry, low density snow, $\log_{10} U$ is a linear function of $\log_{10} Z$. This leads to the following expression

$$U = kZ^n$$

where the "n" and "k" are constants evaluated from the log U log Z plot. Each slab can be described by these constants. It is hypothesized that "n" and "k" give information pertaining to the mechanical behaviour of the slab.

It is useful to reformulate the problem in terms of resistive pressure or hardness. In Hokkaido, Japan, Yosida and his colleagues, using a free falling measuring system, were able to determine the resistive force exerted by various types of snow as a function of time.[6] Figure 4. shows their results for freshly deposited snow. From Figure 4. it appears that the snow compacts beneath a penetrating object and causes the resistive pressure to increase with depth of penetration. If P represents the resistive pressure of the snow, then

$$P = P(Z)$$

and the total force exerted by the snow on a surface, S, is

$$\vec{R} = \int_S P(z)\, d\vec{S}$$

The component of $\vec{R}$ in the z-direction for a 60 degree cone is

$$R_z = \int_0^z P(z) \frac{2}{3} \pi z \, dz$$

The impact energy must perform work according to

$$U = \int_0^z \vec{R} \cdot d\vec{z}$$

which is the scalar integral

$$U = \int_0^z \left[S_0^z P(z) \frac{2}{3} \pi z \, dz \right] dz$$

or in differential form

$$\frac{d^2U}{dz^2} = \frac{2}{3} \pi z \, P(z)$$

but since $U = kz^n$

$$\frac{d^2U}{dz^2} = KN(N-1) z^{N-2} = \frac{2}{3} \pi z \, P(z)$$

and finally solving for P(z)

$$P(z) = \frac{3}{2\pi} KN(N-1) z^{N-3} = K_1 z^{N_1}$$

Mellor[5] gives an excellent summary of previous studies based on similar power relationships between pressure and penetration. The above relationship is consistent with these studies.

For a slab of thickness H, a single coefficient of hardness $\bar{P}$ could be defined as

$$\bar{P} = \frac{1}{H} \int_0^H P(z) \, dz = \frac{3}{2\pi} R \frac{N(N-1)}{N-2} H^{N-3}$$

Because the apparatus developed at Alta gives k and n directly, there seems to be no advantage in using the pressure formulation constants k_1 and n_1. However, $\bar{P}$ will be a useful coefficient to calculate because it gives ordered hardnesses which can be used to verify the drop cone theory.

It is possible to think of (k,n) and $\bar{P}$ as descriptive coefficients of a slab in profile. If it is realized that the expression $U = kz^n$ is only an approximation to the successive discontinuous collapse of the slab's infinitesimal layers the dimensional problems inherent in the power function representation can be reconciled.

In an infinitesimal collapse of thickness Δz, if P is constant

$$\vec{R} = P \int_S d\vec{S}$$

and $$\nabla(\Delta U) = \vec{R}$$

As before, examining the z component for the 60 degree cone

$$\frac{d}{dz}(\Delta U) = P \int_0^{\Delta z} \frac{2}{3} \pi z \, dz = \frac{P\pi}{3} (\Delta z)^2$$

or $$\Delta U = P \frac{\pi}{9} (\Delta z)^3 = \text{(Pressure) (Change in Volume)}$$

which is a dimensionally consistent expression. Then as hypothesized in Figure 5., $U = kz^n$ is the approximation to a set of cubic collapse functions, each dimensionally proper.

The results of the 1967 drop cone experiments are shown in Table 1.

Table 1.

Date	Time	Samples	ρ	k	n	$\bar{P}^*$	Crystal type and Slab Structure	Avalanche Occurrence
2/26	1300	10	0.10	0.55	3.75	11	Heavily rimed dendrites	Sluffs
3/14	1500	25	0.12	0.14	4.40	17	Rimed stellar crystals and graupel	Slab release
3/15	1100	10	0.18	1.20	3.70	21	Slab of 3/14	Stable
3/16	1500	11	0.31	0.39	4.40	48	Slab of 3/14 damp	Stable
3/19	0800	17	0.12	0.31	3.89	9	Heavily rimed assortment and graupel	Sluffs
3/19	1500	25	0.11	1.95	3.36	13	New snow and light winds since 0800	Sluffs
3/29	1500	20	0.17	2.63	3.40	20	Alternate layers, stellar, graupel and stellar	Mostly stable, some release
3/30	1100	15	0.10	0.80	3.52	8	Rimed assortment	Slab release
3/30	1700	28	0.21	35.50	2.56	39	11 00 snow - 1 inch thick sun and wind crust	Stable
4/1	1500	15	0.07	1.26	3.40	10	Clusters of needles and stellars with light rime	Stable
4/13	1100	20	0.21	0.34	4.42	44	Damp snow - one day old	Stable
5/6	1700	20	0.39	0.56	4.30	52	Wet Snow	Occasional wet loose snow
5/11	1500	15	0.11	1.60	3.26	9	Partially melted dendrites	avalanches some wet slab release
5/13	1700	10	0.10	0.28	3.84	7	Moderately rimed stellars	
		100		32	3.9	956	Coarse rock salt crystals	

Conclusions

The results shown in Table 1. cover only the concluding months of one avalanche season. Much more data will be needed before correlations can be worked out between (k,n) and slab release. It is hoped that eventually (k,n) will fit into a complete factor analysis that will include the variables of Figure 1. This will entail the development of extensive "in situ" testing procedures.

The low cost and operational simplicity of the drop cone penetrometer gives it the potential to become a useful soft slab forecasting instrument. Further studies are planned.

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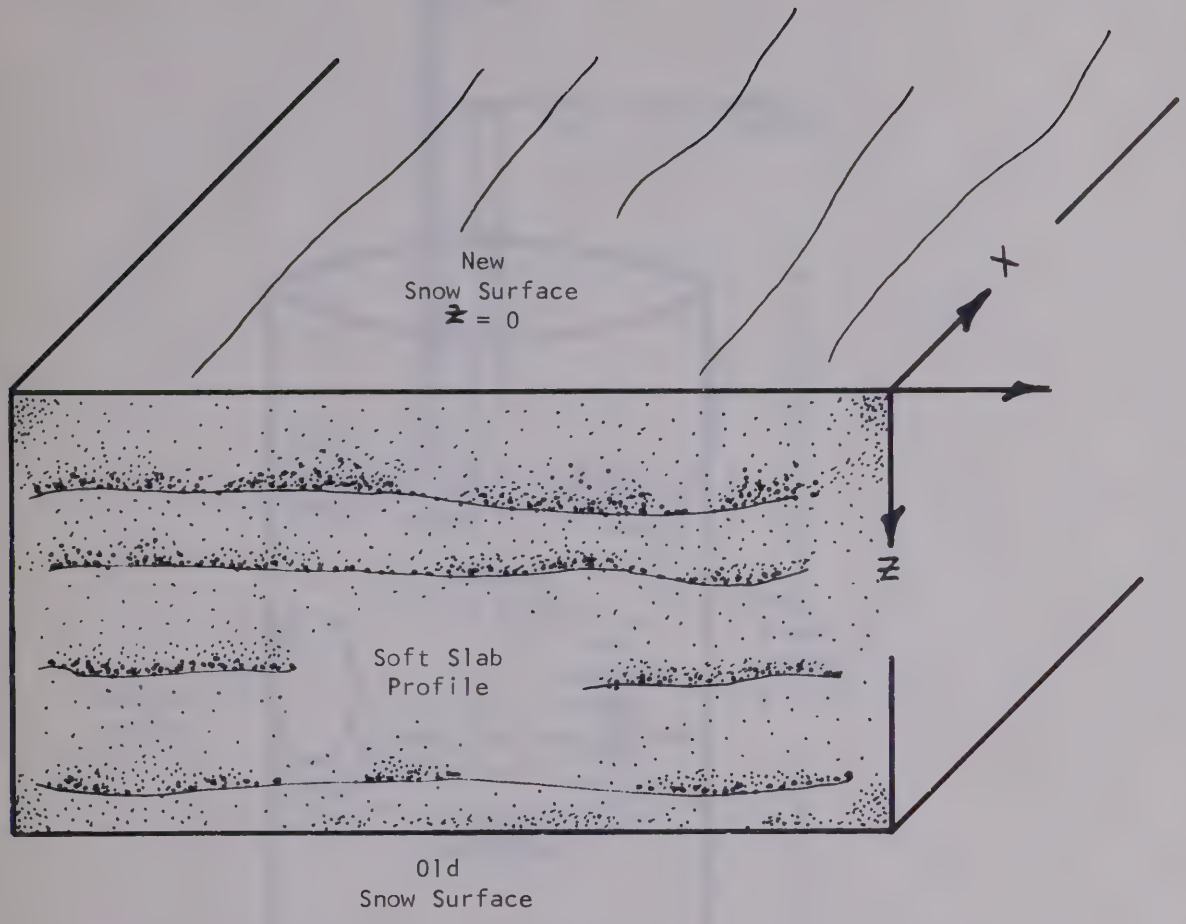
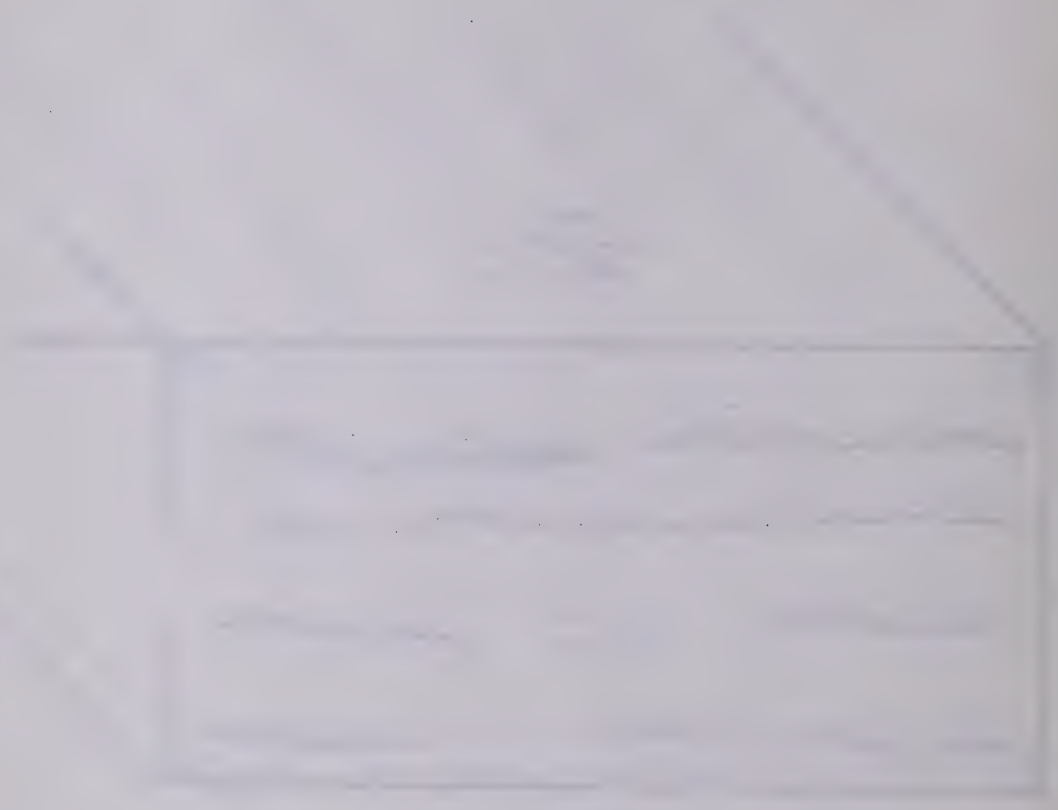


density = $\rho(z)$
strength = $\sigma(z)$
viscosity = $\eta(z)$

temperature = $T(z)$
crystal type = $f_1(z)$
impurity concentration = $f_2(z)$
sintering rates = $f_3(z)$

Figure 1. The first problem. Structure and property variation in the z-direction.



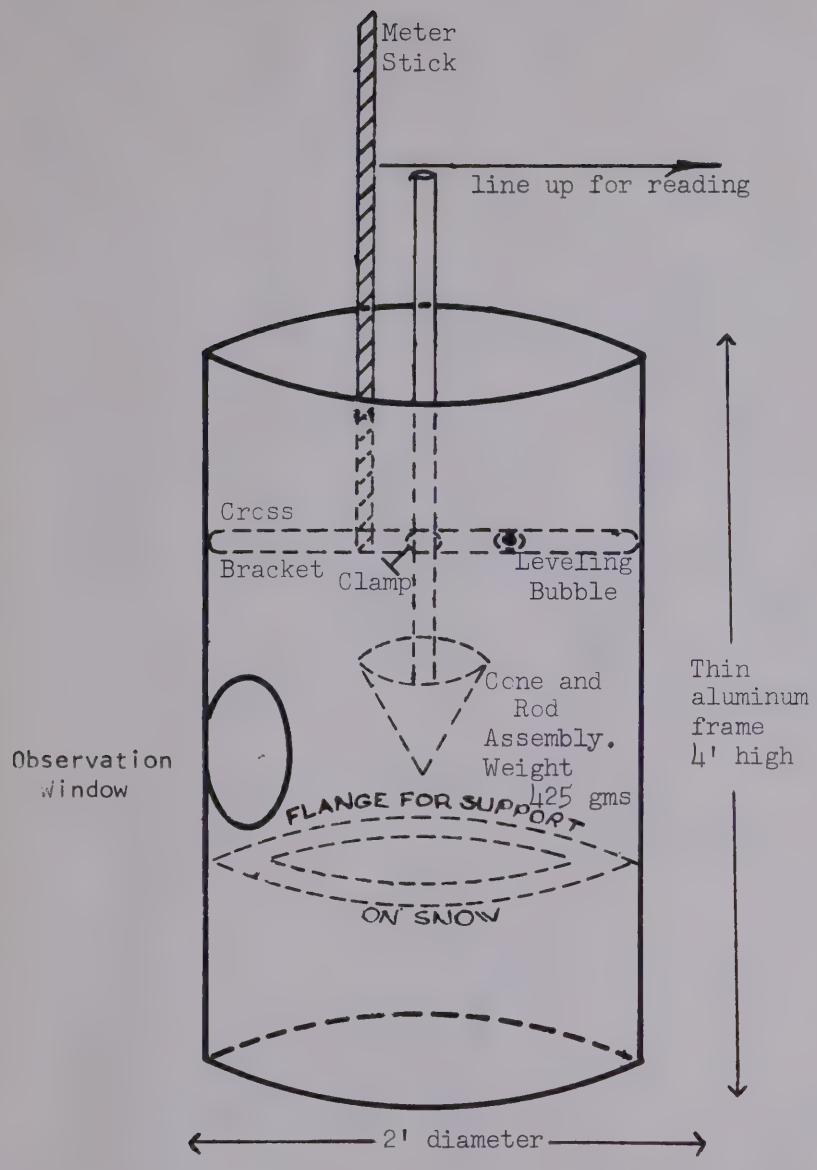


Figure 2. The Alta drop cone penetrometer.

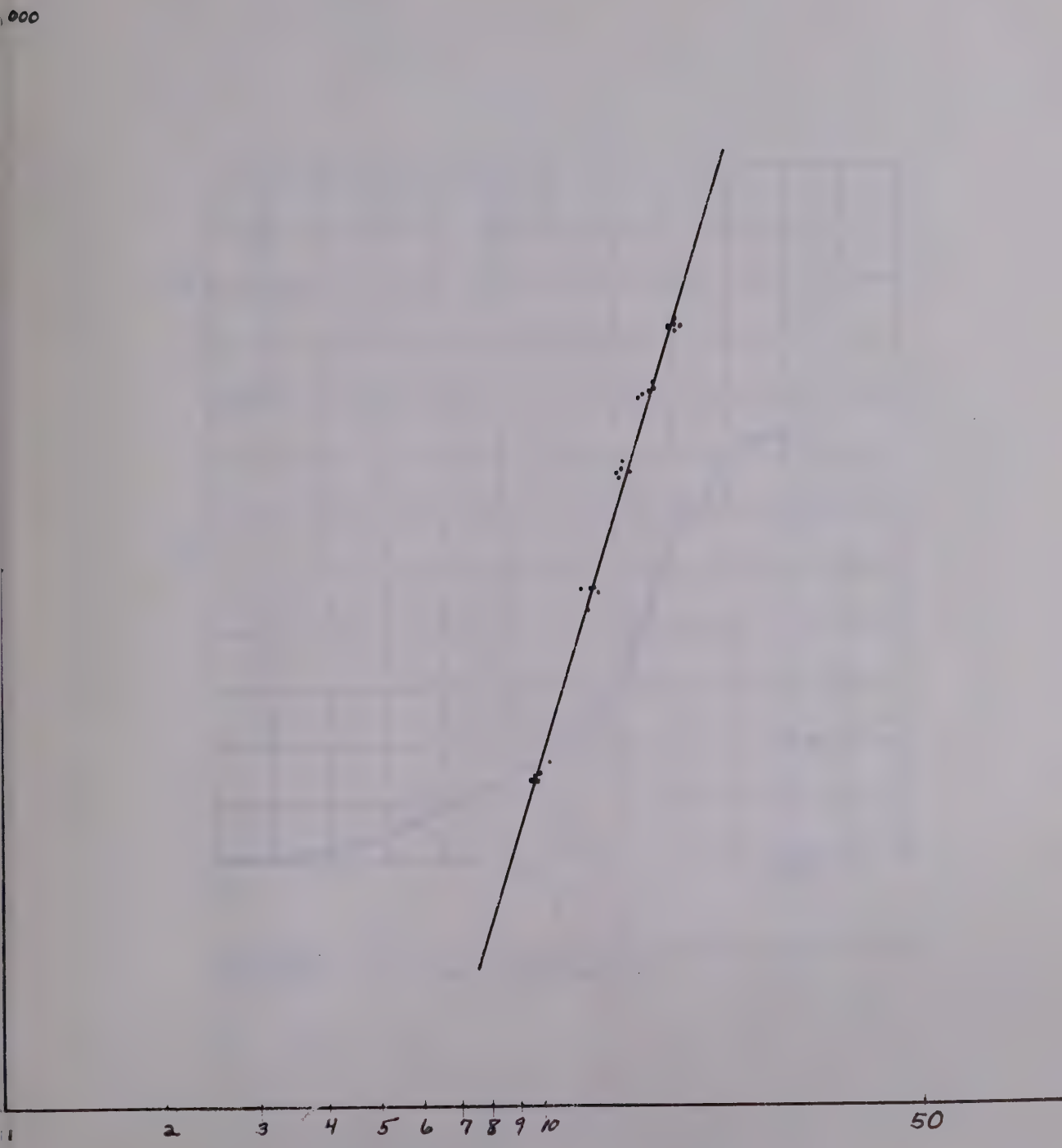


Figure 3. Linear approximation to the data of March 19. Taken at 1500.

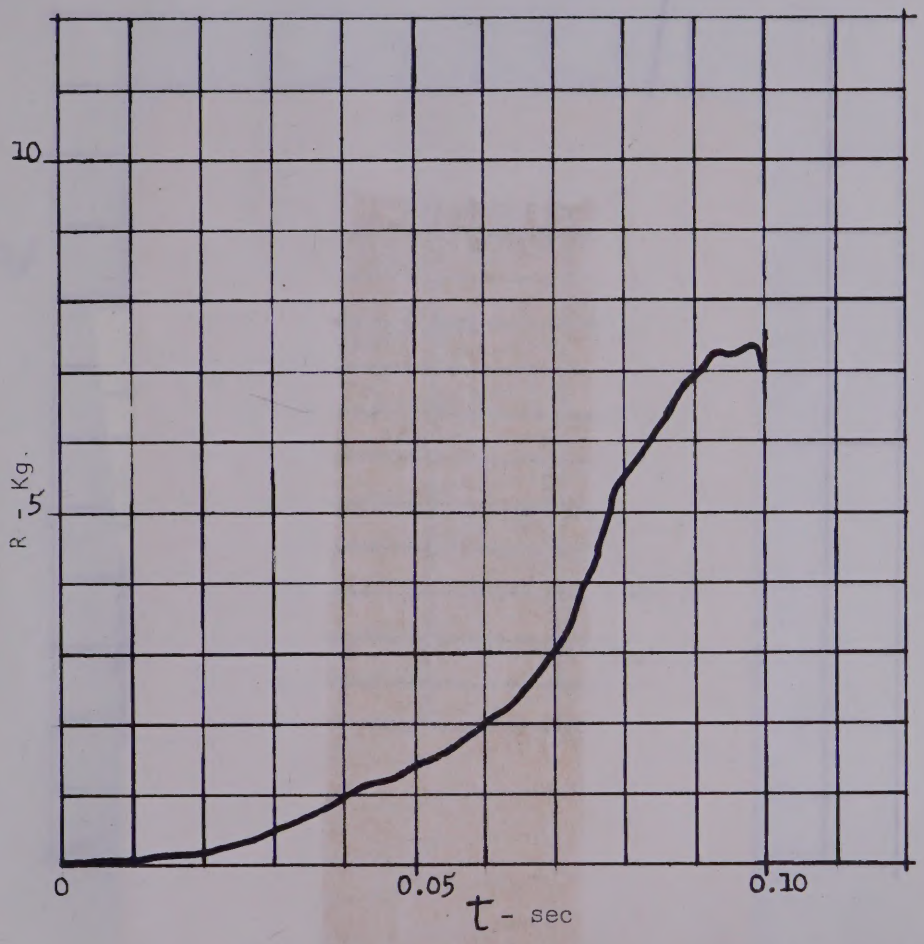
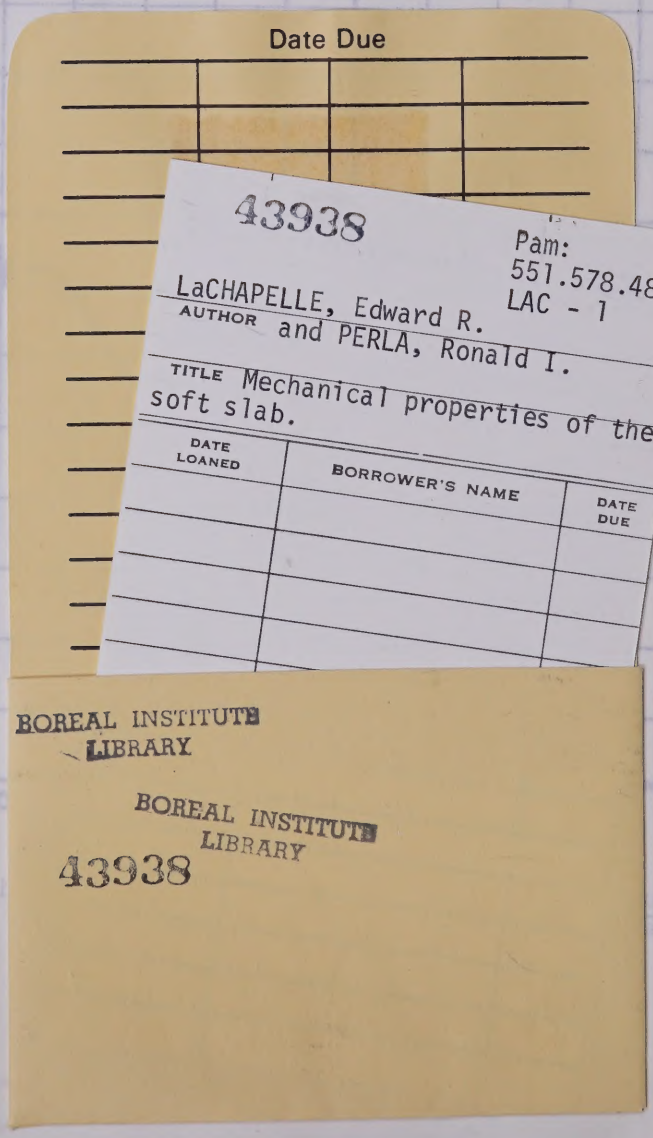


Figure 4. Sketch of an oscillogram showing resistive force as a function of time. (Reference 5.)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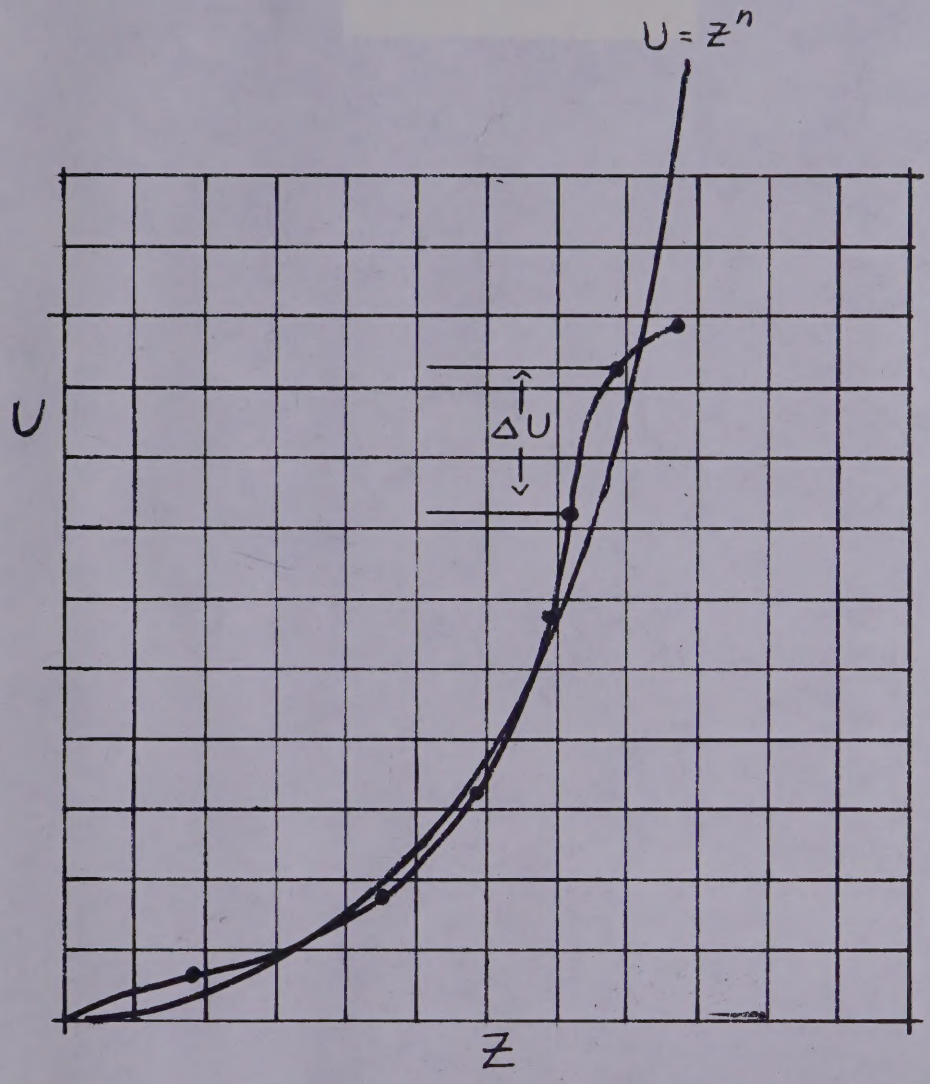

Figure 5. $U = z^n$ is an approximation to a discontinuous function. It is hypothesized that dimensional consistency is achieved if the discontinuous function is a set of cubics.

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